FEASIBILITY STUDY ON COMBINING METAL AND PLASTIC IN 3D PRINTING

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ABSTRACT

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ABSTRACT

The purpose of this thesis was to examine connecting methods for joints created of two dissimilar materials – plastics and metals. Another considerable goal in the project was integrating 3D printing technology to produce a desired joint. The expected outcome of this study was this paper describing of the types of joint connections that were durable, the materials and additive manufacturing methods that could be used within reasonable connectivity strength and a description of the prototype.
There is potential in applying the results of this thesis work for enhancing research on hybrid constructions and for manufacture as well as on-site 3D printing for repair and maintenance purposes.

Keywords Additive manufacturing, Connecting methods, 3D printing, Joint connection, Metal, Plastic, Strength of materials

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Appendices

1 INTRODUCTION

Nowadays lightweight structures for machines and constructions are preferable and pursuit-able thanks to the development of additive manufacturing, or simply regarded as *3D printing*. The reason why keyword lightweight is becoming popular is that conventional structures made of all-metal alloys or all-polymer composites do not satisfy visibility, flexibility and strength requirements within reasonable cost-effectiveness. Hence, hybrids structures consisting of dissimilar materials or even parts behaviour control are chosen.

Thus, the topic of the thesis was to construct and evaluate different connecting methods for metals-to-plastics joints with the help of additive manufacturing in producing plastic parts of the joints. The expected result of the thesis was a report consisting of which connection types should be used for connecting dissimilar materials with different loading cases – tensile, bending and torsion – and prototype laboratory testing results as solid demonstrations.

The hypothesis which the topic based on was that it is possible to connect two dissimilar materials – metals and plastic – into a joint as firmly as two similar materials as well as 3D printing can be used as a manufacturing method for producing parts of the joint. The main question is: How reliable is the plastic-to-metal joint when using 3D printing?
To clarify the terms used in the thesis: *Reliable* means how durable the joint will be when being put on possibly all these loading types: tensile, bending and torsion. *Plastic* is the material of the 3D printing filament such as Polylactic acid (PLA), Acrylonitrile butadiene styrene (ABS), Polyethylene terephthalate (PETG), etc. – made from polyesters or polymers, adjusted chemically to become filament materials – which will determine the material of the 3D-printed object of the plastic-to-metal joint. Meanwhile, *metal* is the material of the manufactured object which its surface has a role of being the solid base for the 3D printing process. *Joint* implies the contacted area of two surfaces of two mentioned objects. Lastly, *3D printing* means the additive manufacturing process of creating a three-dimensional object layer-by-layer gradually.

To achieve these final goals, as it was shown in Figure 1, theoretical studies were handled predominately including the following matters: examining ISO standard for additive manufacturing, stating core knowledge of strength of materials which would be used for analysing the strength of joints, examining available additive manufacturing methods which could be potentially exploited for producing hybrid structures and various features of connecting types for dissimilar joints.

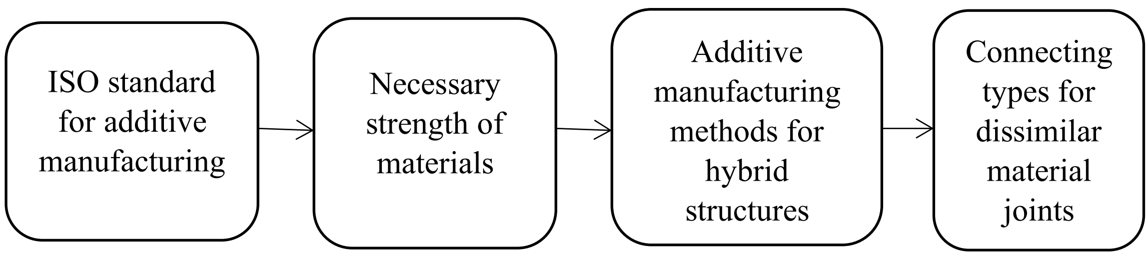

Figure 1. Flow chart of theoretical studies behind the project

After that, prototypes for each connecting type could be considered. This was to be done using Computer Aided Design software i.e. Creo Lib 4.0 first and then solidly created at HAMK Tech Research Unit, Häme University of Applied Sciences (HAMK UAS) and 3D printers at disposal in HAMK UAS, Riihimäki campus. All problems and discoveries were to be reported.

Finally, all the approved prototypes were tested for their tensile strength, bending stress and torsion at the HAMK Tech Research Unity facility in HAMK UAS, the Hämeenlinna campus. Based on the test results, conclusions were drawn and recorded as the results of the thesis project.

2 THEORETICAL BACKGROUND

2.1 Standard EN ISO/ASTM 52900:2015

This document explained the definitions of general principles and terminologies of additive manufacturing (AM). From this ISO standard, there are notable facts that need mentioning as basic knowledge for this thesis work:

Standard EN ISO/ASTM 52900:2015 explains the core principle of AM – successive addition of material - as *process of joining materials to make parts from 3D model data, usually layer upon layer* (SFS EN ISO/ATSM 52900, 2017). This clearly separates AM from other manufacturing principles like subtractive shaping which consists of methods such as milling, turning, drilling, etc. and formative shaping which includes methods like bending, casting, forging, injection moulding, etc.

There are four features which affect the quality of the products of AM:
- Material type i.e. polymer, metal, ceramic or composite
- Principle used for fusion or bonding i.e. melting, curing, sintering
- Feedstock that is used for adding material i.e. liquid, powder, suspension, filament, sheet
- Machine type and its pre-set process parameters

There are two AM processing principles: the single-step process and the multi-step process.
The single step process is defined as *a type of additive manufacturing process in which parts are fabricated in a single operation where the basic geometric shape and basic material properties of the intended product are achieved simultaneously*. (SFS EN ISO/ATSM 52900, 2017)

The multi-step process is defined as *a type of additive manufacturing process in which parts are fabricated in two or more operations where the first typically provides the basic geometric shape and the following consolidates the part to the fundamental properties of the intended material*. (SFS EN ISO/ATSM 52900, 2017)

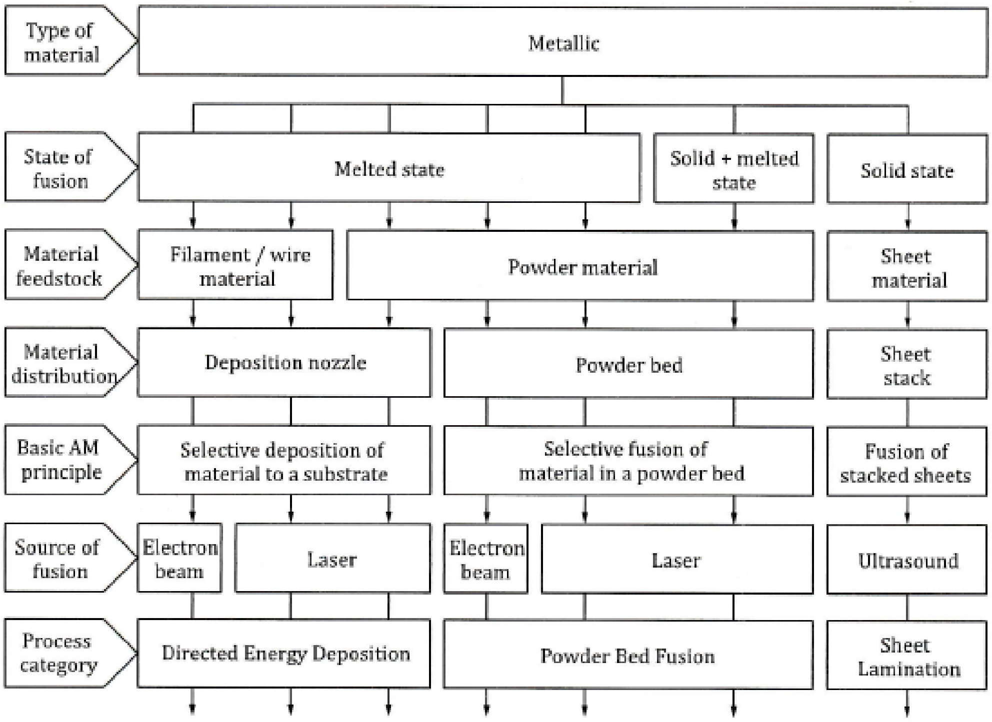

Figure 2. AM single step principles for metallic materials (SFS EN ISO/ATSM 52900, 2017).

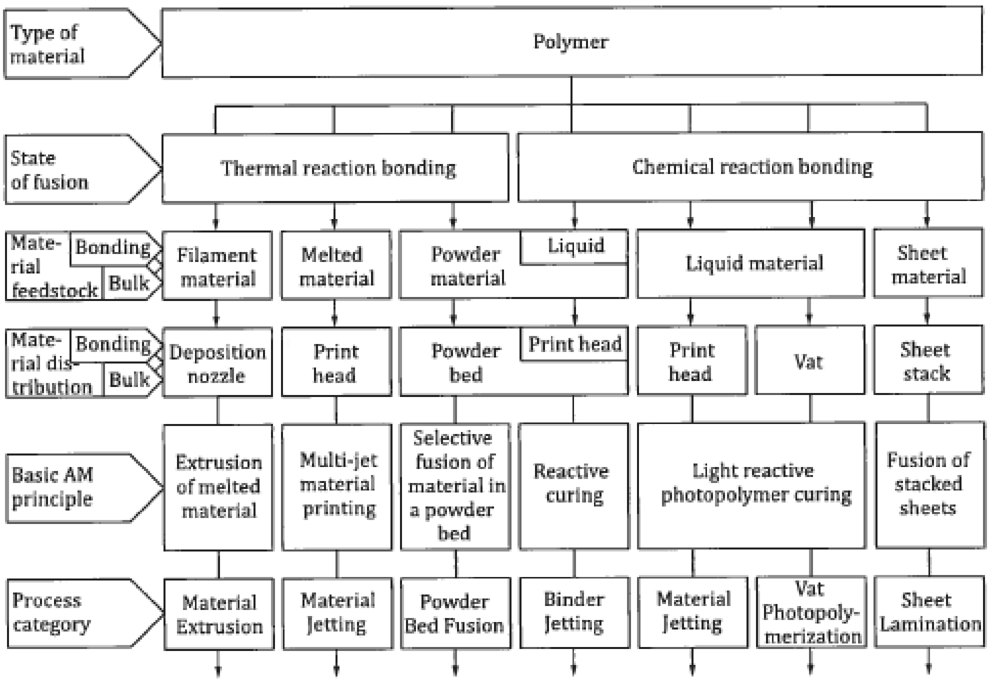

Figure A.3 Overview of single-step AM processing principles for polymer materials

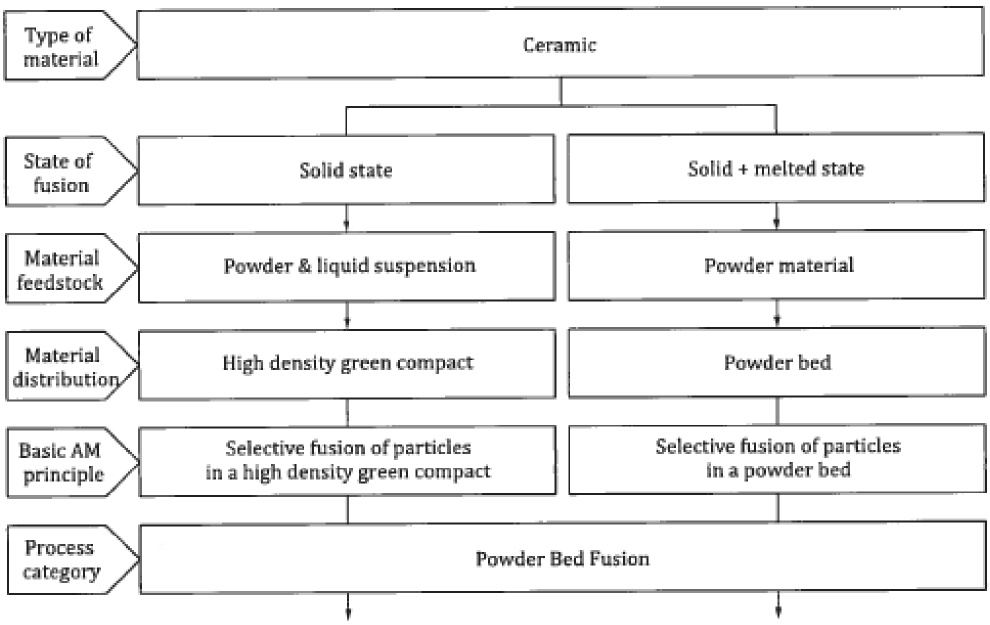

Figure A.4 Overview of single-step AM processing principles for ceramic materials

Figure 3. AM single step principles for polymer and ceramic materials (SFS EN ISO/ATSM 52900, 2017).

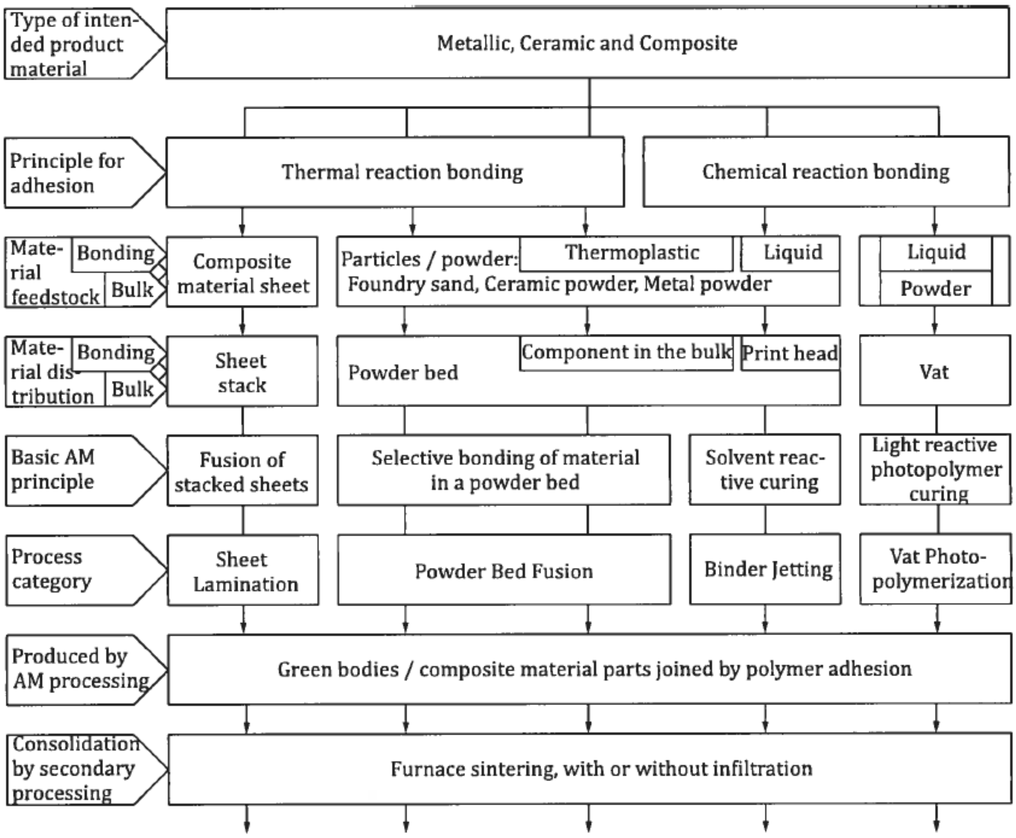

Figure 4. AM multi-step principles for metallic, polymer and ceramic materials (SFS EN ISO/ATSM 52900, 2017).

Figure 2 illustrates the categorization of single AM methods based on different parameters when the chosen material is metallic. From the parameters, manufacturers can choose suitable single AM process to use – whether it is Directed Energy Deposition (DED), Powder Bed Fusion (PBF) or Sheet Lamination.

As shown in Figure 5, DED refers to the category of AM methods which uses thermal energy to melt and fuse material – metal powder and wire filament – within the heated or vacuumed printing area. Necessary bases and material distributing methods are varied accordingly to the operating thermal energy types. To concentrate the thermal energy on the desired area, there are commonly used end-effectors: lasers, electron beams and plasma arcs along multiple axes. (Torta & Torta, 2019)

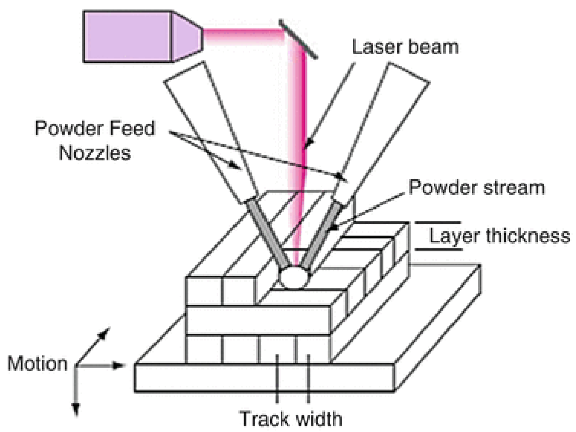

Figure 5. Example of DED process (Gibson;Rosen;& Stucker, 2010).

On the other hand, as shown in Figure 6, PBF focuses on AM methods which use the melting of a powder material – plastic or metal – to fuse particles together. The melting phase can be operated by a heated print nozzle, a laser or an electron beam. Firstly, a thin layer of material is spilled into the print chamber area – the container. Then, the print object outline layer is melted. This action repeats chronically until the required object is formed by melting only the object particles in the spilled layers. The un-melted excessive material is taken away which makes the object visible. (Torta & Torta, 2019)

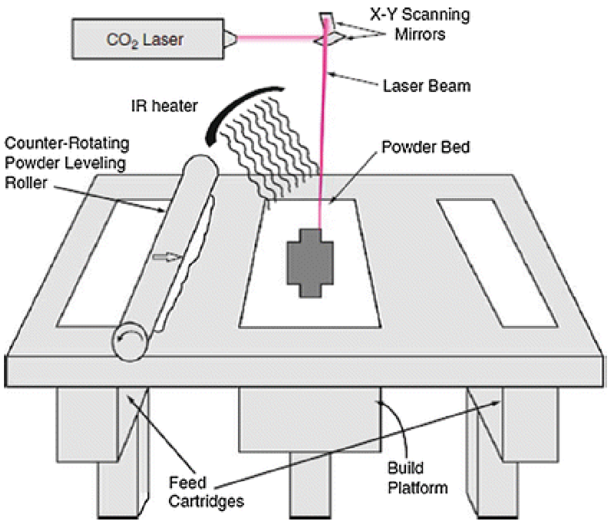

Figure 6. Example of PBF process (Gibson;Rosen;& Stucker, 2010).

Figure 3 illustrated the categorization of single AM methods based on different parameters when the chosen material is polymer or ceramic. If the material is polymer, from the parameters, manufacturers can choose suitable single AM process to use – whether it is Material Extrusion, Material Jetting, Powder Bed Fusion, Binder Jetting, Vat Photo-polymerization, and Sheet Lamination. If the material is ceramic, even though only the Powder Bed Fusion process is suitable, manufacturers should also notice which basic AM principles to practice.

Figure 4 showed the categorization of multi-step AM methods for all chosen materials such as metallic, ceramic or composite. Although the process can be different based on established parameters, all products should be consolidated by secondary processing.

2.2 **Necessary terminologies and formulas of strength of materials**

Strength of materials is the study of observing structural behaviours of solid objects e.g. beams, trusses, joints, shafts under stresses and strains when there are loads or forces acting upon them (Den Hartog, 1977).

With the plastic-to-metal joint, to study its strength of materials, the author decided to treat it as a simple case of a joint consists of an axial loaded bar – the 3D printed plastic part – with one end has rigid support which was the metal part of the joint. The chosen demonstrated unit length was millimetres (mm) as it is the standardized unit for engineers worldwide. Hence, all the units of the following features were deduced accordingly to the chosen unit length. Here was the list of notable mechanical properties needed to be concerned and calculated after the strength tests were conducted:

1. Normal stress σ

   This is the normal force acting over a unit area of the cross section of the object. Its unit is N/mm^2 or mega-Pascal (MPa):

$$\sigma = \frac{F}{A} \tag{1}$$

2. Normal strain ε

   When a normal force is applied on an object, there is going to be elongation per unit length. This is a unit-less value:

$$\varepsilon = \frac{\Delta L}{L} \tag{2}$$

3. Stress-strain curve

   When there are normal stress σ and normal strain ε on the object, it is possible to make a graph which monitors the stress and strain value through time during the strength tests, which is called 'stress-strain curve'. The examples of some stress-strain curve of different materials were shown in Figure 7. From left to right in Figure 7, the materials are a) medium-carbon steel, b) alloy steel, c) hard steel and d) non-ferrous alloy. It was clearly visible that the curve varied for various materials.

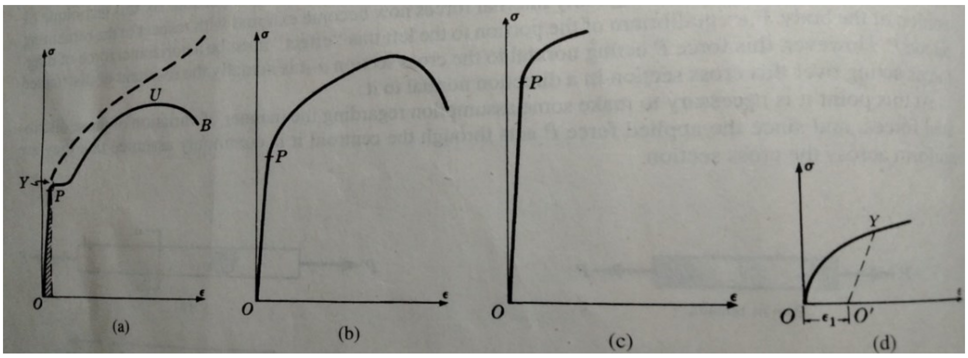

Figure 7. Examples of stress –strain curve (Nash & Potter, 2011)

4. Modulus of Elasticity E

   From the stress-strain curve, it is visible that the relation between stress and strain is linear; given the strain has small value, and this is called *Hooke's law.* In Figure 4, it could be seen that point P marked the limit of the linear relation between stress and strain. Hence, E is the ratio of stress to strain; its unit is the same as normal stress - MPa and calculation of *Hooke's law* can be written as:

$$\sigma = E \times \varepsilon \tag{3}$$

   The term *elasticity* means the ability of material of to keep its original form when there is stress on the object so that there is no perpetual deformation when the stress is removed completely. Hence, there is elastic limit for each material and it is almost coincident with mentioned point P.

5. Tensile strength/Ultimate strength

   Point U in the far-left graph in Figure 4 marked the tensile strength, which is the maximum point of the stress-strain curve. From that point, the stress decreases.

(Nash & Potter, 2011)

From all the mechanical properties mentioned above, it was comfortable to find the value needed for analysing by combining (1), (2) and (3). For instance, to find the change in length of the material, it could be found by:

$$\Delta L = \frac{FL}{EA} \tag{4}$$

2.3 **Potential AM Methods for joining dissimilar materials**

2.3.1 Cold spraying

Cold spraying (CS) is an AM method which uses high-velocity particles of provided feedstock to shoot directly to the surface of substrate – the object which is 3D printed upon. The particles would attach to the surface so that a coating layer could be created.

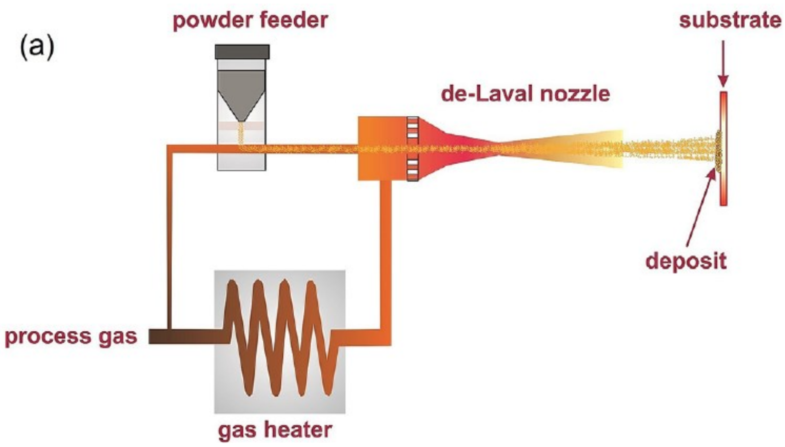

Figure 8. Schematic diagram of the original cold spraying system (Assadi;Kreye;Gärtner;& Klassen, 2016).

Figure 8 demonstrates the principle of CS focuses on making the particles with 10 – 50 μm diameter of the powder-shaped feedstock stick tightly to the surface of substrate at or higher critical velocity which is typically over 1200 m/s. This could be done thanks to means of pressurized above 1 MPA and preheated gas - nitrogen (N_2) or helium (He) – that reaches through a converged nozzle which would accelerate the particles from the powder feeder to mentioned velocity. The duration of the process is around 100 nano-seconds. The nozzle will move accordingly to the control program to cover all the surface of substrate per demanded.

When the particles hit the surface, due to their high-velocity characteristic, the phenomenon *material deposition* occurs. It means the strong bonding between the surface and the particles transpires and make all the particles attach tightly to the surface. The impact must be consecutively and quickly done to increase the bonding strength of the deposition.

There are different types of CS system: high-pressure CS, low-pressure CS, vacuum CS and laser-assisted CS. One notable thing is when metals powder is suitable for all CS system, ceramic or composites powder can only be suitable for vacuum CS because other CS system would create fractures or breakages of ceramic/composites particles.

While the advantages of CS can be acknowledged such as thick coatings, little-to-no oxidation thanks to tightly lingered particles make no space for oxygen to penetrate the coating layer, cold microstructure & reduced cooling requirement all thanks to low heat input of CS in process aftermath, no bulk particle melting due to quick movements of the nozzle and possible on-site AM for repairing purposes; the downsides that need to be improved are: limited applications for ceramic and composites powder, expensive helium gas, high gas consumption due to maintaining the velocity of the particles from the powder feeder.
(Assadi;Kreye;Gärtner;& Klassen, 2016)

2.3.2 Ultrasonic welding

In Figure 9, ultrasonic welding acts upon a simple principle: creating bonding state for two parts by high-frequency vibrating energy with the help of clamping force. Preferable material shape for joining parts is sheet. The direction of applied ultrasonic oscillation depends entirely on the type of the upper sheet – if it is metal, then the oscillation is parallel to the welding force; if it is plastic, the oscillation would be perpendicular to the welding force.

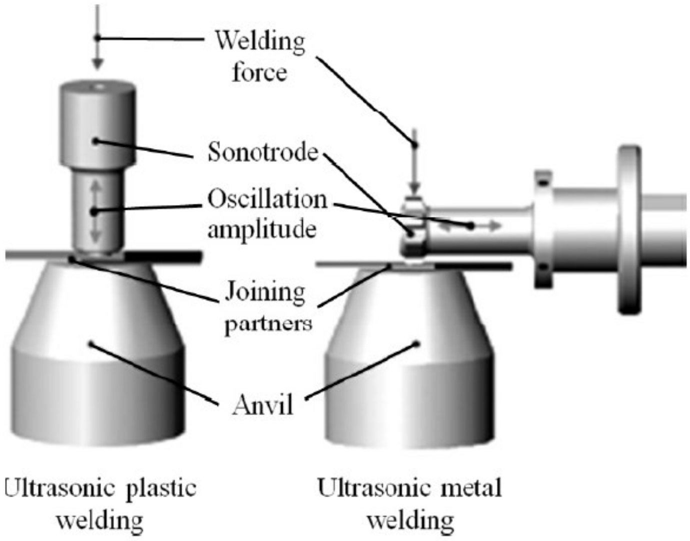

Figure 9. Ultrasonic welding schematic diagram(Kah;Suoranta;Martikainen;& Magnus, 2014).

This method is considered promising for joining dissimilar materials because of its low heat input which will minimize the melting effect on plastic parts, better contact between two surfaces of joining parts, fast processing duration and increased joint strength thanks to the uniformly mix between plastic and metal parts in the joining zone.

But improvements are needed for these disadvantages: thickness of the parts affects greatly the quality of welded joint; preferably for these new techniques, 1-2 mm thick is optimal; limited effectiveness on high-melting-point materials, both plastics and metals, and limited flexibility because most of the joint are put in overlap position to ensure the heat absorption.(Kah;Suoranta;Martikainen;& Magnus, 2014)

2.3.3 Laser radiation

Laser radiation (LR) is an AM method which will use thermal energy to melt the materials which are put in the one-on-top-the-other position in the contact area of materials or the *joining zone* and hence, the bonding will be created.

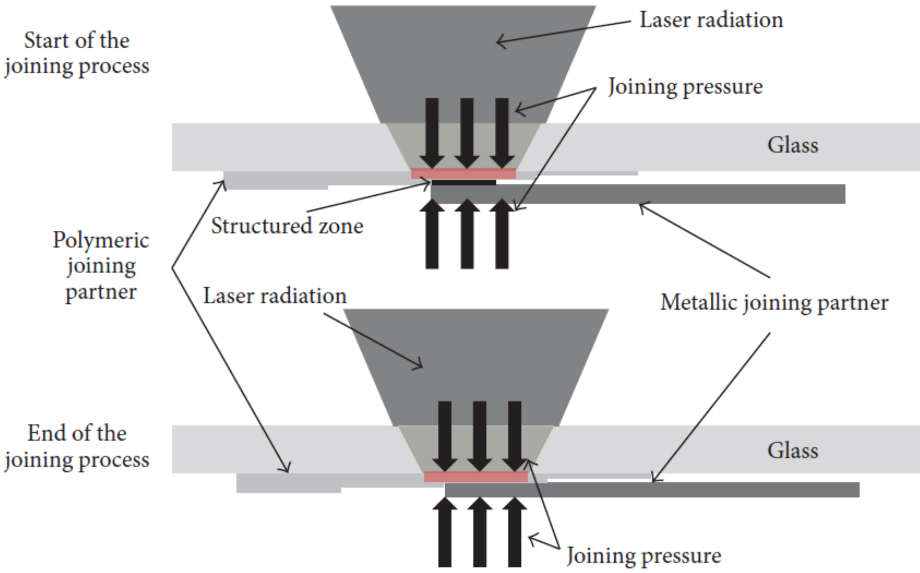

Figure 10. Schematic diagram of LR process (Hopmann;Kreimeier;Keseberg;& Wenzlau, 2016).

According to Figure 10, the principle of LR can be described as follow: A partially or fully laser-transparent plastics joining component will be put on top or beneath of the metallic partner, along with a glass layer to find out the effects of the LR process afterwards. When the laser radiating beam operates, the metallic part will act as the laser energy absorber and heat up the plastic part within their *joining zone*. When the plastic part is internally heated above its melting point, bonding forces appears and a hybrid joint is created. The beam will move to cover entire joining zone to further strengthen the bonding forces.

In this method, the transmittance level of the plastics & the absorption rate of the metals are important factors which need to be considered when choosing the materials. However, the LR methods has its advantages i.e. suitable for all polymers, short time process, well-exploited the metallic strength properties; the corrosion rate due to outer environment of the metallic part of the hybrid joint increased after the process, breaking force significantly reduced in weather-involved conditions.
(Hopmann;Kreimeier;Keseberg;& Wenzlau, 2016)

2.4 **General AM procedure**

This AM procedure was needed for manufacturing plastic parts for study cases. The generalized process can be visualized as in Figure 11:

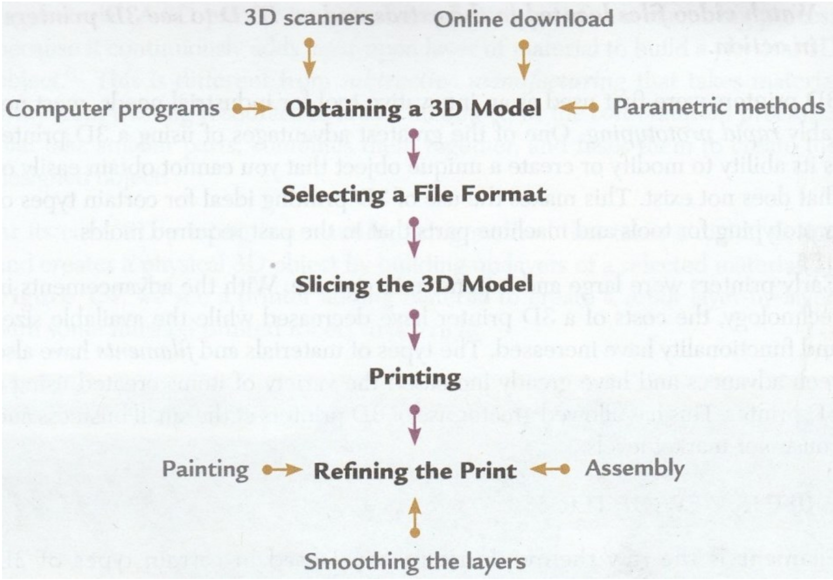

Figure 11. General chart of AM procedure (Torta & Torta, 2019).

The author realized Figure 11 was just a simplified version and should not be strictly followed without modifications, so the author decided to cross-refer with another source so that the finalized AM procedure for the thesis work was streamlined suitably without excessive movements. The finalized procedure was written according to the following steps:

1. Draw a CAD file of the 3D model desired to be produced by AM process.
The 3D geometrical features of all parts must be designed well in CAD software. In this thesis work, Creo Lib 4.0 will be utilized for creating parts.

2. Convert to .STL file (STereoLithography)
All 3D printers accept STL file format, and converting CAD file format to STL can be conducted comfortably within the CAD software itself.

3. Transfer to 3D printing software and adjust the STL file suitable for manufacturing
General adjustments of the STL file should be conducted so that it is in correct volume, position and orientation for layer-adding.

4. Set up the printing machine parameters
Material constraints, energy source, layer thickness, timing, set up supports for special geometrical shapes of the parts, etc. are all important layer-adding parameters that need attention and possible modifications.

5. Layer-adding commences
The process starts now. It is semi-automated so the human aspect is minimized. The process duration depends on the platform height, layer height, material deposition rate.

6. Removal and cleaning
After the object is manufactured, conduct the removal of surplus features and clean up the platform of the 3D printing machine.

7. Further aftermath
In some cases, additional coatings or chemical cleaning for the base/the printed object should be conducted. This step is highly necessary on case-by-case basis. It can be passed when no complications found in the object.

8. Application
The printed object is ready to use. It is possible that some properties of the object can be different compared to the ones manufactured by conventional methods.
(Gibson;Rosen;& Stucker, 2010)

2.5 **Connecting methods for dissimilar materials**

In this chapter it is examined concerned how two surfaces of dissimilar components can be joined so that afterwards the joint would operate normally in normal working conditions. The most common methods are mentioned here as follows:

2.5.1 Connecting by adhesives

This is a joining method that depends on the intermolecular bonding strength between the dissimilar parts and the polymeric adhesive for joint creation after the adhesive goes through physical actions as two parts push the adhesive tightly against it and each other or chemical reactions as the adhesive reacts to the surfaces – or substrates of both parts. The structure of this type of joint was shown in Figure 12. When using this method, the crucial factors are the surface quality of the substrates and the geometrical shape of the adhesive joint which will determine the bonding strength. Therefore, pre-treatment for joining surfaces of parts like solvent sanitizing, abrasion, contact angle should be conducted thoroughly so that the boundary layers – created by all chemical reactions among the substrates with the adhesive – contain minimized impurities. Examples of different geometrical shapes of adhesive joints are shown in Figure 13.

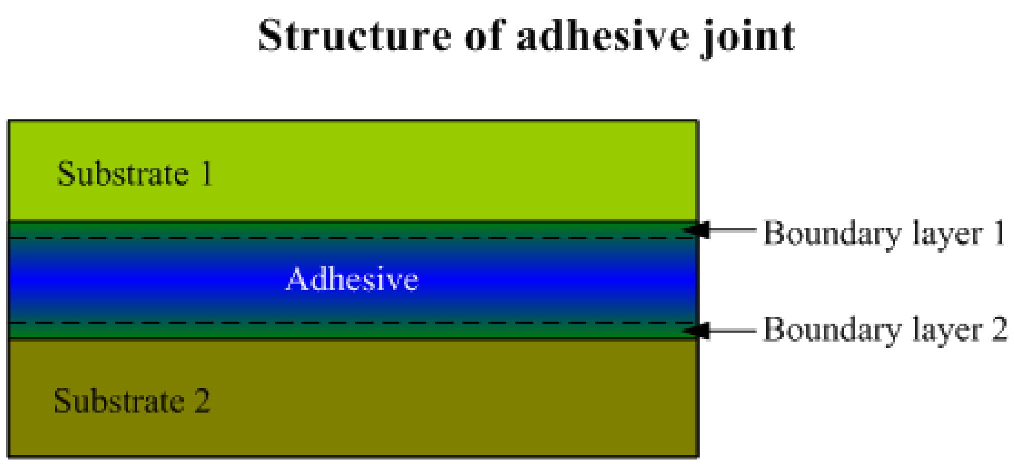

Figure 12. Structure of adhesive joint (Kopeliovich, 2014).

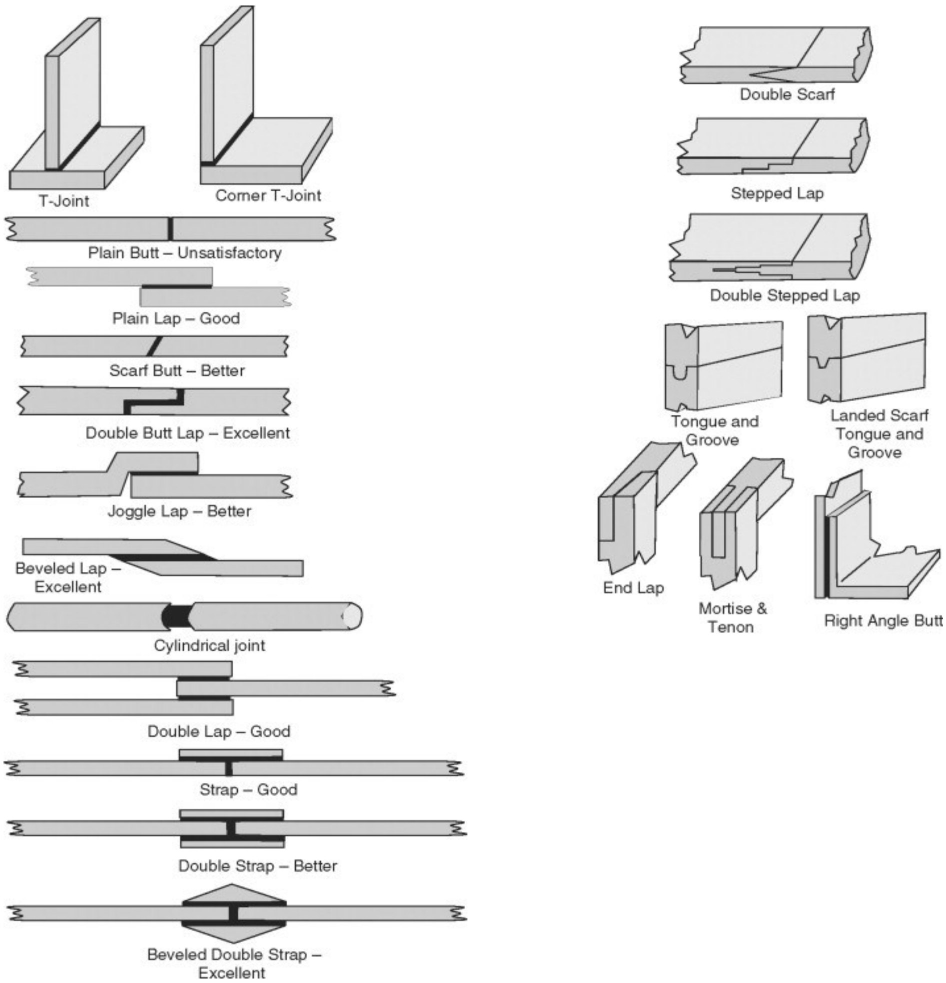

Figure 13. Geometrical shapes of adhesive joint (Troughton, 2008).

This method gains its popularity because of the ability of adhesives to withstand static loads & stress distribution and reduce total net weight of the component after joining. However, the disadvantages are also noticeable: vulnerability to environmental corrosion e.g. humidity, temperature change, zero chance of disassembling the parts without damaging them and low predictability for the duration of the joint.
(Kah;Suoranta;Martikainen;& Magnus, 2014)

2.5.2 Connecting by mechanical mechanism

This method covers all types of clamping two components together without fusing the surfaces by using screws, rivets, bolts & nuts and even creating geometrical interlock. The procedure may include pre-heating rivets so that after fastening process the rivets will shrink to further clamp the joint, material removal like drilling holes/making screw threads in metallic parts before the joining process.

The method is widely used thanks to its simplicity, durability and mass-product chain-friendly. Also, it can be automated and flexibility for adjustment which means the joint can be designed to move freely in one specific axis movement or accept standardized geometrical tolerances.

Be good as it may, preferably this method is used for metal-to-metal joint, so there are disadvantages when it comes to plastic-to-metal joint: increased component load on the plastic parts replacing metal parts could cause corrosion and fractures, limited position for the metallic parts as they have to be placed under the plastic parts to resist deformation and elongation as much as possible.(Kah;Suoranta;Martikainen;& Magnus, 2014)

2.5.3 Connecting by heat

This method covers different kinds of welding: metal arc welding, gas tungsten arc welding, gas metal arc welding, submerged arc welding, laser welding, ultrasonic welding, friction spot welding, etc. The core principle is that two parts need to be welded are put together and the contacted surfaces called heat affected zone HAZ will be heated up to the melting point of the materials. Then, the end effector of welding equipment created a melted substance to enhance the coalescence of melted properties in the HAZ occurs and welding joint is created (Kah;Suoranta;Martikainen;& Magnus, 2014). Normally welding works best with two similar materials because the melting points of these materials would be closed to each other. In Figures 14 & 15, some mechanisms of this method were shown.

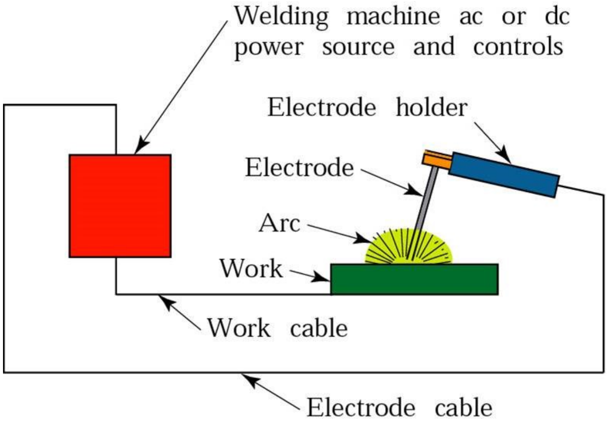

Figure 14. Principle of metal arc welding (Youssef, 2017)

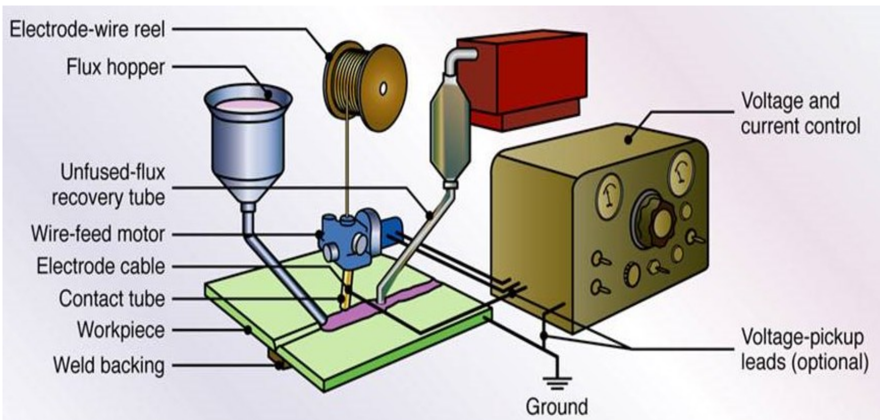

Figure 15. Principle of submerged arc welding (Youssef, 2017)

However, since the requirement is to make a plastic-to-metal joint, the only feasible industrial welding types are laser welding, ultrasonic welding and spot welding because other conventional welding would melt the plastic part significantly due to the long heat exposure duration before the melting point of the metal parts is reached. On the other hand, in this thesis work it is plausible the joint would only be created by combining two or more methods i.e. connecting by adhesives and heat, connecting by mechanical and heat together, not just one method alone.

2.6 Materials for joint prototypes

The material of 3D-print cylinder is PLA with 1.75m thread diameter of the raw material's form. This material is popularly used for its following features: tough, environmental friendly because it was made from recyclable raw resources i.e. sugar cane, corn-starch. (3dprintingforbeginners, 2013).

In Table 1, some material properties of PLA are shown. Noticeably, the print bed temperature could be 0ºC, which is a good feature as preferably the metal surface is not preheated because it was time-consuming to heat up metal objects. The working temperature of PLA – 190ºC to 230ºC – must be remembered for setting working parameters of the 3D printing nozzle of the Dobot arm. The author also did not have any prior experience of AM operating, hence this material is the easiest one to start working with, plus the high strength and medium durability were considered good advantages.

Table 1. Materials properties of PLA (Torta & Torta, 2019)

Working temperature (general)	190ºC – 230ºC
Print bed temperature (general)	0ºC – 60^{oC}
Strength	High
Flexibility	Low
Durability	Medium
Advantages when used + Easiest material for beginners to work with + Less prone to warping compared to ABS + Available in many variants including full range of colours, translucent, and glow in the dark + May produce a sweet aroma that smells like candy when heated	Disadvantages when used + Can be strong but brittle + Attract water molecules and become brittle at times, making it difficult to print if not stored correctly + Water saturated PLA needs a higher extrusion temperature

The material of the metal cube was S235 steel. This material was chosen because of its high manufacturability with simple-shaped parts and S235 steel was one of the most commonly used structural steel in manufacturing industry. Although the material properties of the cube did not play a vital role in this thesis work, the author still noted some mechanical features of this structural steel type: its suitability for welding, yield strength 235 MPa, tensile strength 360 – 510 MPa, elongation 26%. (SFS EN 10025-2, 2019)

3 FEASIBILITY TEST IN THE PROJECT

3.1 Tests of joint connecting methods

The joint consisted of two parts: a metal cube and a plastic cylinder. Before the parts were manufactured, they were designed in Creo as shown in Figure 16. In CAD models, the dimensions of the cube were 50x50x20 mm, the dimensions of the cylinder were ø30x150 mm. The reason the size of the cube was determined like this is as shown in Figure 17. The most effective operating area of the Dobot arm was most focused in front of the Dobot arm within the borders of two concentric half-circles so that the Dobot arm was not damaged by the movements of its arm joints. The axial length of the operating area was 114 mm (315- 201 = 114). Hence a cube of 50x50x20 mm was suitable for putting it right into the center of the operating area.

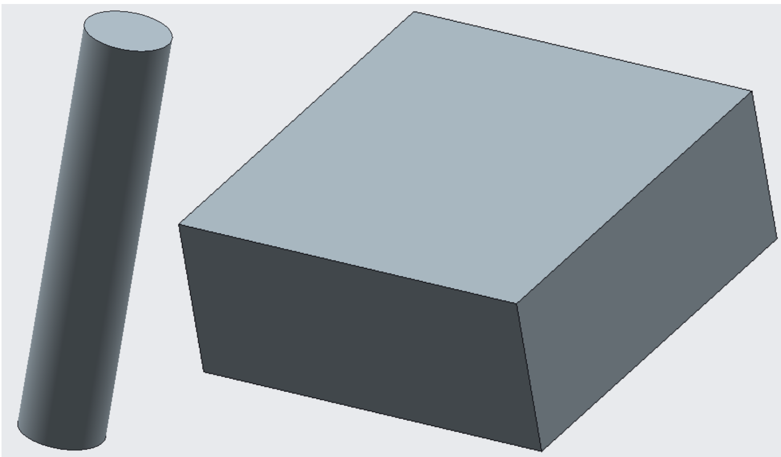

Figure 16. CAD models of plastic cylinder ø30x150 mm (left) and steel cube 50x50x20 mm (right)

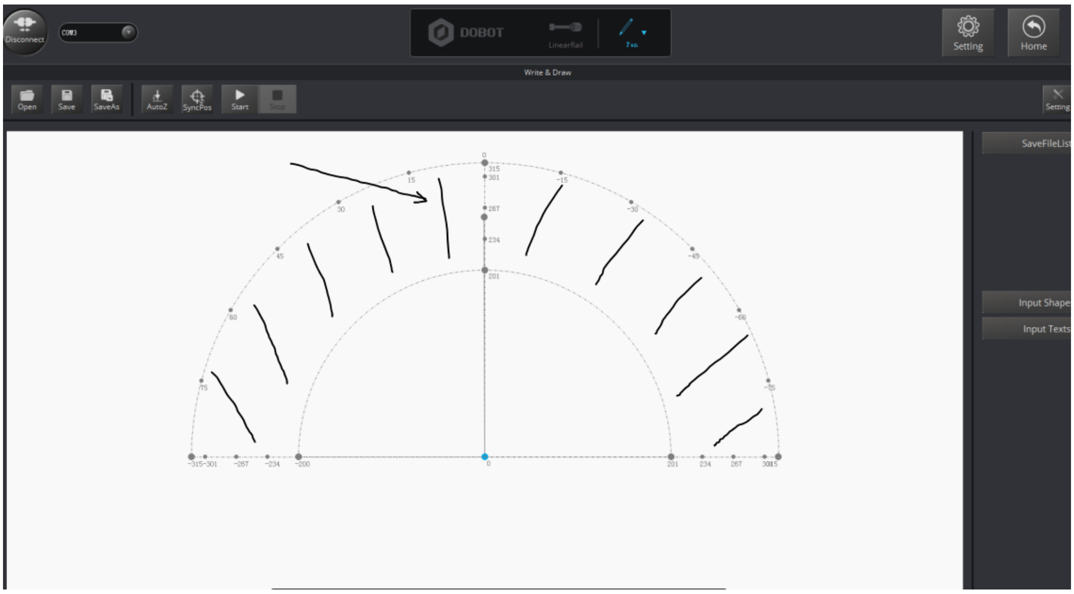

Figure 17. Effective operating area of Dobot arm (Shenzhen Yuejiang Technology Co.,Ltd, 2012)

However, after observing the duration of 3D printing the cylinder completely, the author decided to make the cylinder small-scaled instead of full size as a CAD model to reduce 3D printing time – to print a 150mm height cylinder with a diameter of 30 mm, the simulation anticipated a 22-hour printing session and took a lot of filament and supervising time. The cube was on the contrary decided to be manufactured in full size.

In Figure 18, after removing rust and dirt – the remnants caused by the cutting process by the vacuum box, all the surfaces of the steel cube were not finished to increase the surface roughness value Ra (SFS ISO 4287, 2000) comparing to a normal finished surface, which means the surface of the cube had visible holes. The main purpose of these holes was to enhance the bonding ability of melted plastic in the 3D printing process into the metal surface as the first layer of 3D-printed plastic filled up the holes, so when the other layers were printed, the pressure would press the first layer tighter onto the holes, thus accumulate joint connectivity of contacted zone when the plastic part cooled down. All Ra values were recorded accordingly to Mitutoyo SJ210 series measuring device's catalogue (Mitutoyo, 2012).

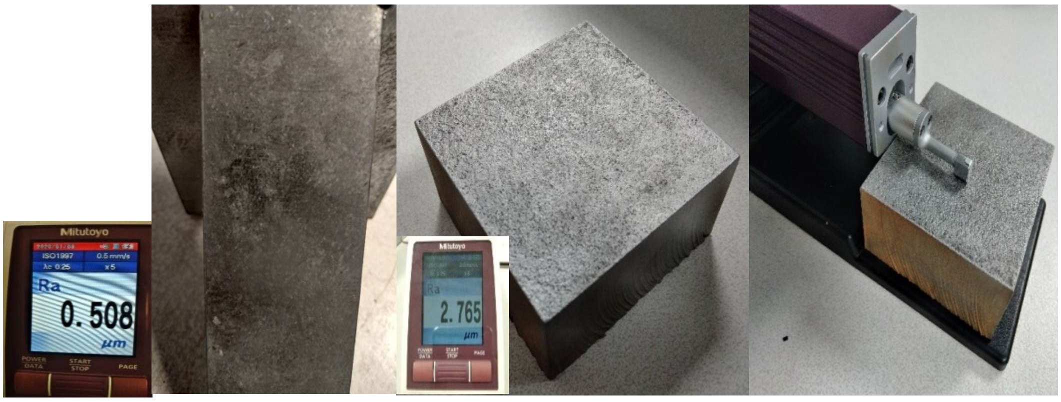

Figure 18. *Ra* value of finished steel surface (left); one manufactured unfinished metal cube (water-cut, rust blown) (middle); example of an operating surface roughness device (right)

The parameters set for measuring surface roughness of the S235 cube were shown in Table 2. These parameters were mostly in default mode of the device, so further research involved in measuring surface roughness can repeat them comfortably.

Table 2. Set-up parameters of SJ 210 for measuring surface roughness (Mitutoyo, 2012)

One factor needed to be tested of the cube which was whether the cube should be preheated to the PLA's working temperature or not. If the cube was heated, it would be heated up to 200ºC which is the same temperature as printing degrees of PLA material and then it would cool down in room temperature. All the scenarios for the cube needed to be experimented accordingly to the three mentioned connecting methods and even their combinations.

After reading the Dobot user manual for setting up a 3D printing procedure (Shenzhen Yuejiang Technology Co.,Ltd, 2012), the completed set up was established as shown in Figure 19. It can be seen from left to right: the computer, the raw PLA material disc, the feeder, the Dobot arm and the metal cube ready for printing.

Measuring speed	0.5 mm/s
Returning speed	1 mm/s
Skid force	Less than 400 mN
Applicable standard	ISO 1997
Evaluation parameter(s)	Ra
Cut off length λc	0.25 mm
Number of sampling lengths (x n)	x 5

Figure 19. Completed set up for 3D printing

The plastic cylinder was 3D printed directly on the unfinished surface of the cube by Dobot arm, controlled by Repetier Host which is third-party software linked with DobotStudio by computer. The reason for using Dobot arm instead of using 3D printing machine was the difficulties of setting up the height of the surface – it could only be done by adjusting the G-codes manually line-by-line. This was considered time consuming for the author as the author did not have prior experience in programming G-codes for 3D printing. Moreover, all 3D printing machines of HAMK would be damaged when contacting metal surfaces, the printing bed would operate abnormally when the cube's weight being put on it. Furthermore, since the thesis work covered several experiments, it would be better to operate 3D printing procedures with Dobot i.e. easier emergency stops, instant adjustments if needed.

One considerable factor was the feed rate of raw material and the flow rate of the 3D printing nozzle. To create the plastic-to-metal joint, both the feed rate and the flow rate should be equally high speeded so that a strong forced-upon descending flow of PLA plastic would attach to the surface of the cube.

Hence, the conditions of the 3D plastic printing tests were to be conducted for creating joint prototypes are displayed in Table 3. These parameters can be used repeatedly for further researches after the thesis work was completed.

Table 3. Conditions of 3D printing tests

	Steel cube’s state	Presence of adhesive: Glue	Nozzle temperature	Nozzle diameter	Flow rate	Feed rate	Surface roughness value *Ra*	Layers’ printing speed
Test No.1	Not preheated	No	200ºC	0.4 mm	120 mm/s	120 mm/s	2.765 µm	4 mm/s
Test No.2	Not preheated	Yes	200ºC	0.4 mm	120 mm/s	120 mm/s	2.572 µm	4 mm/s
Test No.3	Preheated	No	200ºC	0.4 mm	120 mm/s	120 mm/s	2.232 µm	4 mm/s
Test No.4	Preheated	Yes	200ºC	0.4 mm	120 mm/s	120 mm/s	2.765 µm	4 mm/s

Figure 20. Heating temperature setup (left) and mechanical workshop’s stove (right)

In Figure 20, the stove was set to 200ºC. The stove started heating and when the black indicator hit the red one, the desired heating temperature maintained for one hour to heat up the cube completely.

The temperatures of all four stated-above tests were measured by a Sato SK-1250MC thermometer (Sato Keiryoki Mfg.Co., Ltd.). All outcomes were recorded, no matter positive or negative as it could become invaluable cornerstone for further research.

3.2 Results of the tests of joint connecting methods

3.2.1 Test No.1

In Figure 21, it can be seen that the cylinder was printed but no desired metal-to-bonding was created and no melted plastic was detected in the holes on the unfinished surface of the cube. The author anticipated that the plastic would not attach to the steel surface and this result was a solid proof.

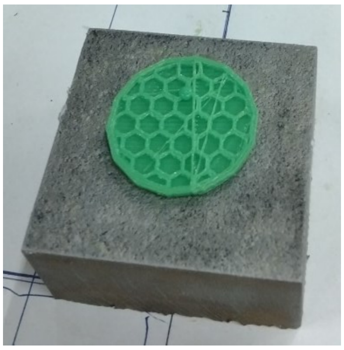

Figure 21. Negative result of test No.1

3.2.2 Test No.2

The test had the same working conditions as test No.1, except glue was applied to the cube's surface. However, as in Figure 22, the result was negative; it was easy without force to get the cylinder off the surface.

Figure 22. Negative result of test No.2

3.2.3 Test No.3

After the cube was preheated for one hour in the stove and put into the ready position, the 3D printing procedure occurred. The first layer of plastic was overheated and deformed. As can be seen in Figure 23, the result was negative; no plastic-to-metal connection was detected.

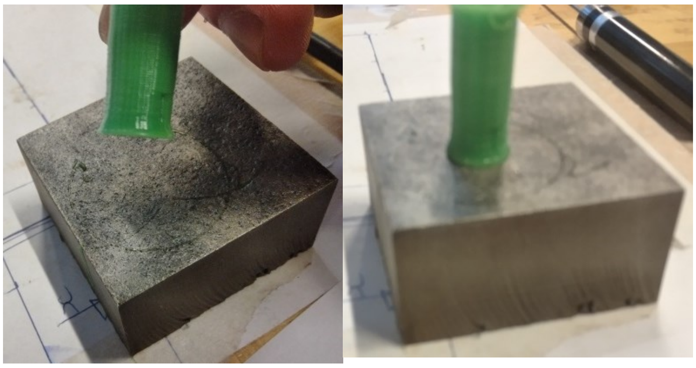

Figure 23. Negative result of test No.3

3.2.4 Test No.4

The first layer was created with little-to-none deformation, the adhesives on the preheated surface of the cube worked well in assisting the creation of plastic-to-metal connection, only minor deformation was detected on the first layer as it cooled down slower than the other layers which did not contact the steel surface directly. After cooling down, the bonding stayed firmly. Hence, a cylinder was formed. Therefore, Test No.4 was acknowledged as positive since a plastic-to-metal joint was established as can be seen in Figure 24.

Figure 24. Recorded temperature during cool down process of the steel surface (left) and the printed cylinder (right)

However, during the 3D printing process to achieve the desired small-scaled height of the cylinder, the nozzle was stuck at one point and the melted filament refused to flow out. The emergency stop was pushed, so the height of the cylinder stayed at a short value. This phenomenon repeated with the other two prototypes. Still, based on the result of Test No.4, two more cylinders would be created and reserved for later strength tests. All prototypes were captured in Figure 25.

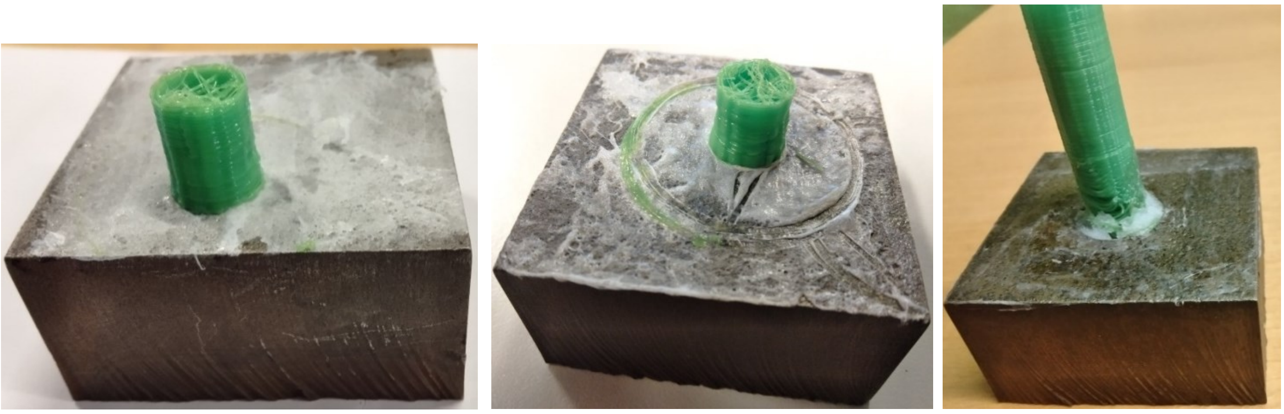

Figure 25. Three created plastic-to-metal joints following the parameters of Test No.4

From left to right, the author marked the prototypes as prototype (1), prototype (2) and prototype (3). The dimensions of the cylinders were recorded in Table 4. There was no need for recording the dimensions of the cubes because they were identical 50x50x20 mm.

Table 4. Dimensions of the 3D printed cylinders

	Height h (mm)	Diameter d (mm)
Prototype (1)	13	11
Prototype (2)	11	11
Prototype (3)	39	11

To summarize, here are the specimen manufacturing features so that in further tests these notions could be acknowledged and based on for setting up the parameters of the tests:

1. For metallic part of the joint:
    - The cube was designed to fit the most effective operating zone of a 3D printing kit.
    - The cube was cut from the raw material with the notion of leaving the surfaces unfinished to obtain a higher value of surface roughness
    - Noticeable challenges: None
    - Recommendations for further tests: Stay with simple geometry
2. For plastic part of the joint:
    - The cylinder was designed to provide simple respective contact area with the metallic part
    - The cylinder was 3D printed by 3D printing software which was built in DobotStudio software
    - Noticeable challenges: Time-consuming and material-costly AM process Not enough filament material, nozzle blockade, significant deformation of the first layer of the cylinder
    - Recommendations for further tests: higher nozzle diameter i.e. 1mm, allow the metallic part to cool down longer time i.e. 10 minutes before applying adhesives and starting to conduct AM process, large supply of 3D printing filament, use 3D printers instead of Dobot arm and its 3D printing kit.

3.3 **Durability tests**

3.3.1 Setup of durability tests

At the HAMK Tech facility in Hämeenlinna, according to the test supervisor, it turned out that the heights of prototypes (1) and (2) were not sufficient for the end-effector of the test machine to grasp. Hence, only prototype (3) was put to the tests. Also, the platform available for the test machine could only perform the tensile test, not the bending and torsion ones. Hence, only the tensile test was performed with one prototype of out three.

The parameters for prototype (3) were:

- Loading type: tensile
- Direct of applied load: vertical upwards
- Test machine: Zwick/Roell Z005 with a maximum test tensile load of 5kN (Zwick/Roell).
- Speed of applied load: 1 mm/min
- End-effector: Gripper

Figure 26 illustrates the setup of the tensile test: the 3D printed cylinder of prototype (3) was put through a centered hole of a thick steel sheet which was vertically fixed to the U-shaped anvil – the sheet prevented the steel cube from going upwards along with the cylinder when tensile load was applied.

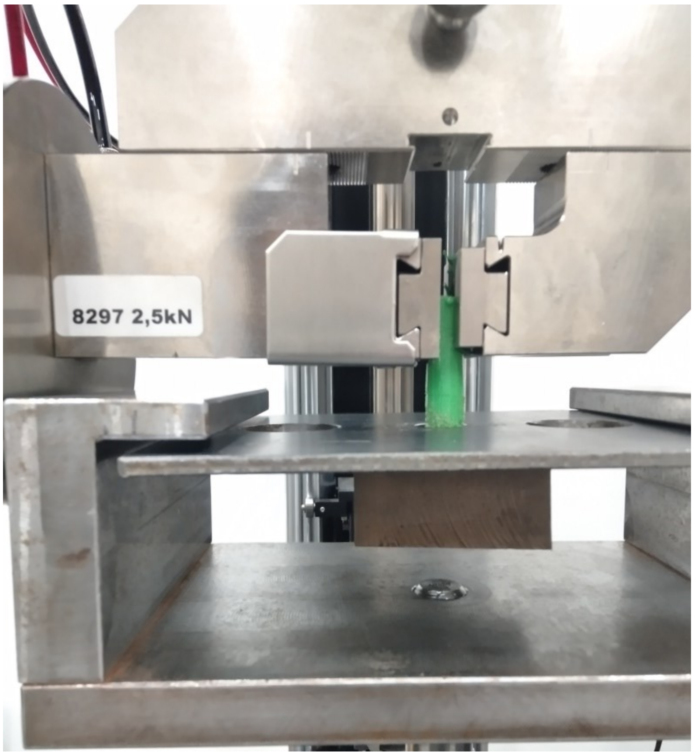

Figure 26. Setup of tensile test for prototype (3)

There was one incident with the cylinder in the test: The gripping force of the end-effector deformed the cylinder when it grasped the cylinder. However this was considered not to affect the test result and the test was continued.

3.3.2 Results of durability tests

The result was: the cylinder elongated and had visible fractures near the rigid-fixed end, as shown in Figure 27. This phenomenon was predicted as the load was axially distributed and there was no other rigid or residual support along the cylinder.

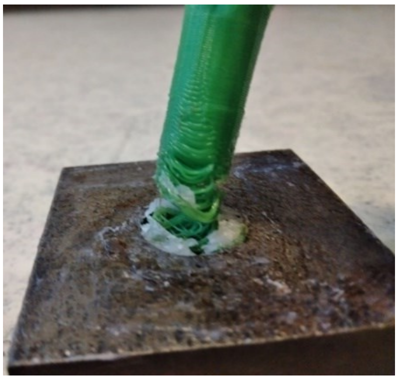

Figure 27. State of prototype (3) after durability test

The force-strain curve was recorded as shown in Figure 28. Also in Figure 28, it could be seen that the ultimate strength of the cylinder was 52.3 N; the total elongation of the cylinder was 7.3 mm. The elastic limit was when (force; strain) = (40N; 1.6 mm).

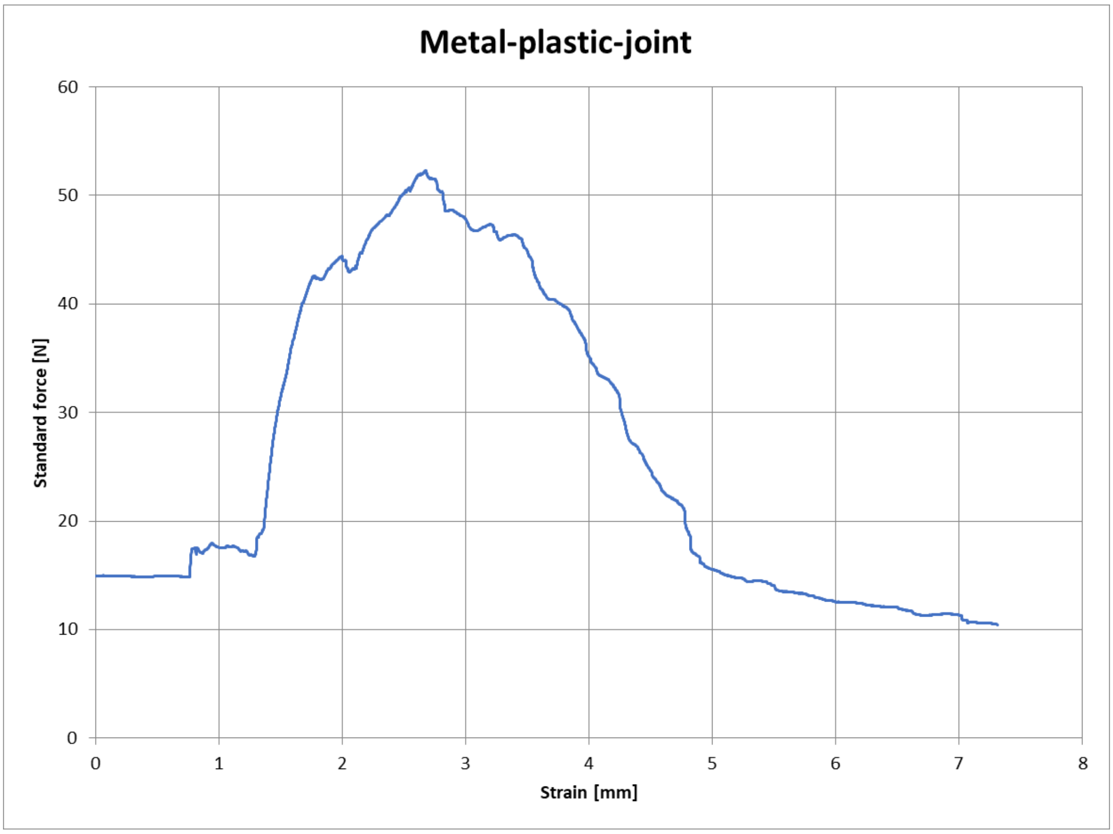

Figure 28. Force –strain curve of cylinder made from PLA material of prototype (3)

4 FINDINGS

4.1 Analysis of durability test result

From the curve in Figure 26 it was possible to calculate other mechanical properties of the cylinder. The modulus of elasticity was calculated using combinations of formula (1) and (3) in chapter 2.2:

$$E=\frac{\frac{F}{A}}{\varepsilon}=\frac{\frac{40N}{\pi\times(\frac{11}{2}mm)^2}}{\frac{1.6}{39}}\approx 10.26\ MPa$$

This was quite a low value of PLA material. It could be explained that since the *infill* value was 20% when the cylinder was 3D-printed, the material gap between as well as within the layers was increased so the elasticity was consequently decreased compared to a 100% *infill* cylinder. Meanwhile, the change in length at the fracture point was calculated by using formula (4) in chapter 2.2:

$$\Delta L=\frac{52.3N\times 39mm}{10.26MPa\times\ \pi\times(\frac{11}{2}mm)^2}\approx 2.1\ mm$$

During the 0 – 0.7 mm phase, the strain increased but the force stayed the same. Then the curve became approximately linear and the deformation started when the elastic limit was reached. However after the elastic limit, the curve did not increase or decrease gradually. This can be explained so that the mentioned incident during the setup phase made the body of the cylinder not to sustain the even force distribution on its body anymore. Hence, some parts of the cylinder could still withhold higher force applied whereas others could not.

The fracture occurred long after the ultimate strength point was reached. In Figure 26, it can be seen that was the longest strain – from 3 mm to 7.3 mm – of elongation actually fell in the decrease phase of the applied force until fracture point. It proved the good flexibility of PLA.

However, the brittleness feature of PLA was a disadvantage. The result would be clearer to be analyzed if the incident caused by the end-effector did not happen. The metal cube did not suffer any deformation. It is quite clear that to improve the plastic-to-metal joint, the material needed to be improved was the 3D printed one.

Overall, the reliability of the plastic-to-metal was visible – high enough strength, medium flexibility. Deformation occurred only on the body of the plastic part. Brittleness was proved to be a major disadvantage.

4.2 Recommendations for further research

To create a plastic-to-metal joint, both adhesive and heat are needed to be used. For the metal part of the joint, it has to be pre-heated or heated at a low temperature during the AM process to manufacture the plastic part of the joint. The surface of the metal part should not be finished with too fine quality to enhance the bonding ability between the metal and the plastic. The applied adhesive on the metal surface should be able to tolerate high temperatures as the working temperature of plastic filaments is high.

For the plastic part, the material of the filament needs to be chosen carefully. If the researcher has little-to-no experience with 3D printing, commercial materials such as PLA, PETG are suitable choices, but if they have more experience with 3D printing, composites consisting of various materials which bring out the best feature of each other should be chosen. During the phase of setting the parameters for printing the plastic part, parameters such as the flow rate, the feed rate, the infill percentage, the moving speed of the nozzle must be adjusted sensibly to prevent unexpected incidents resulting in filament leakage/block. To improve further research; less brittle plastic material for the filament i.e. ABS should be tested, ratio of the flow rate to feed rate should circle around 1:1 ratio, the infill rate should be increased to 50% or more to withstand higher loading forces without crumbling, the contact area of plastic and metal surfaces should be increased to achieve a firmer bond and the geometry of the contact surfaces should stay circular as in two-dimensional geometry, with the same length, a circle provides the largest area.

Finally, the researchers should acquire background knowledge of using G-codes for 3D printers so that they could adjust the zero-level where the AM process should start and indicate in which position the plastic part should be printed on the metal surface. The author did work well with the Dobot arm and its 3D printing kit, but only because the author had no prior experience with 3D printers.

5 CONCLUSIONS

The thesis discussed how to create a plastic-to-metal joint with 3D printing technology and examined its reliability. Different theories of the AM procedure, strength of materials and connecting methods were studied prior to the thesis work. Various scenarios of manufacturing the joint were tried and recorded as failures – either there was no desired bonding phenomenon occurred or when it did, the deformation of the plastic part was not acceptable because the joint structures changed significantly – it was not an axial loaded bar with one end fixed rigidly on a metallic support anymore. Hence, the analysis of the strength of materials was not thorough as expected.

To improve, it is advisable to lengthen the cool-down time for the metallic base before starting to operate the AM process on its surface. By doing this, the plastic filament would solidify quicker and the deformation of the plastic part would be minimized.

However, consequently, one positive test result was recorded and it gave the answer to the main question of thesis: It is possible to create a plastic-to-metal joint base with a combination of two methods: connecting by heat and connecting by adhesives. After having the prototypes at disposal, there was only tensile strength test performed on one suitable prototype due to the insufficient height of the other two prototypes. It proved that the reliability of the joint was detectable but it must be improved by having more qualified specimens – three or more – to obtain more statistically valid results.

Nevertheless, all the results and achievements were recorded and considered as good outcomes. They would serve as background information for further research so that everyone would be aware of which theoretical aspects to count on, what has been tried and what not, how the experiments were conducted and recorded so that s/he would not have to initiate them again.

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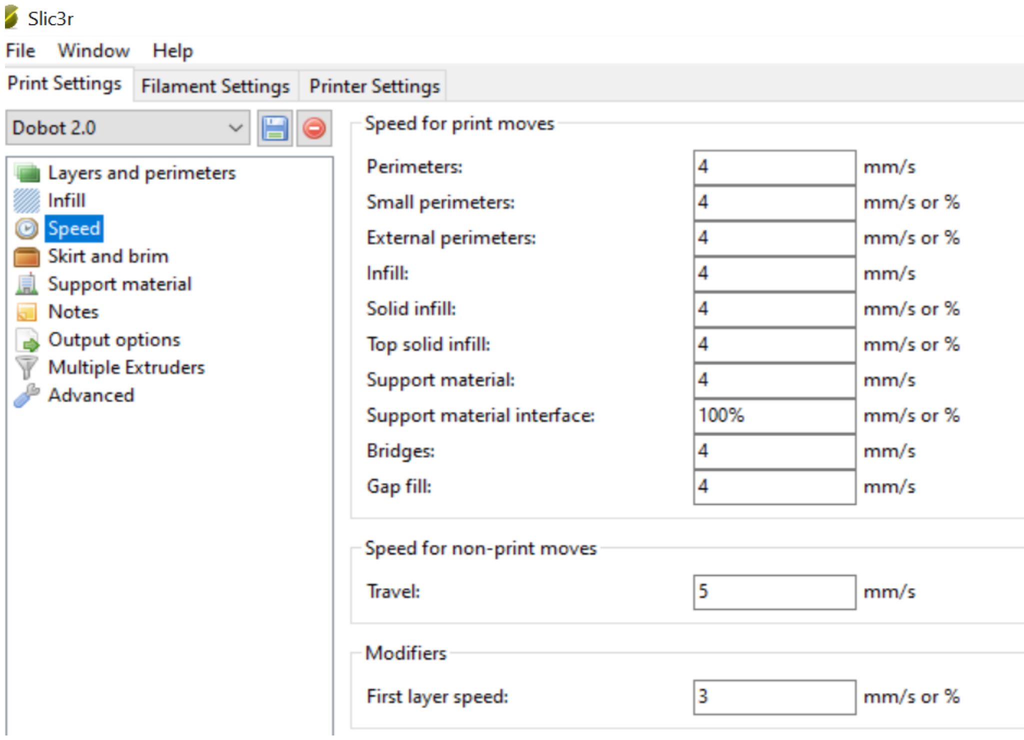
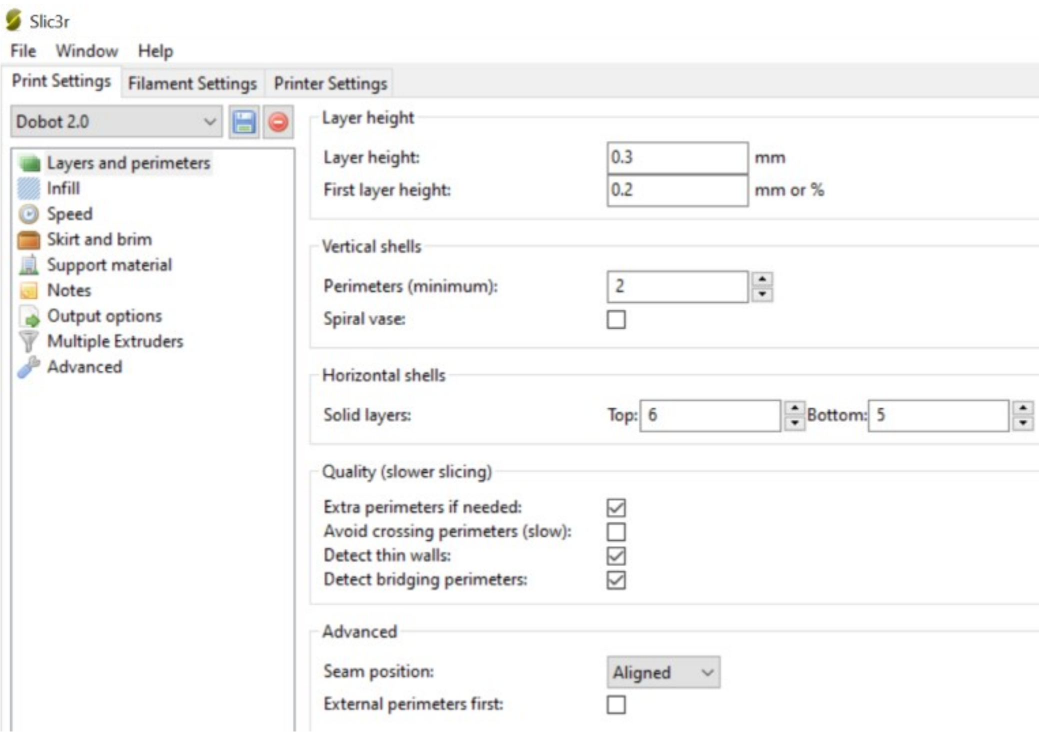
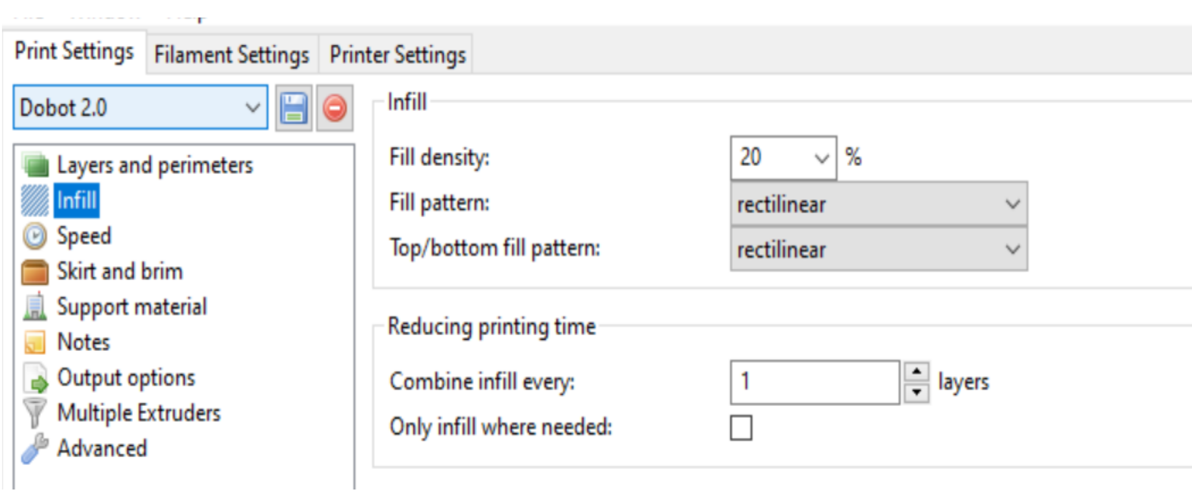
Appendix 1/1

PRINT SETTINGS OF 3D PRINTING IN REPETIER HOST SOFTWARE





Appendix 1/2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Filament Settings
Printer Settings
Dobot 2.0
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Speed
Skirt and brim
Support material
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Advanced
Infill
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%
Fill pattern:
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Top/bottom fill pattern:
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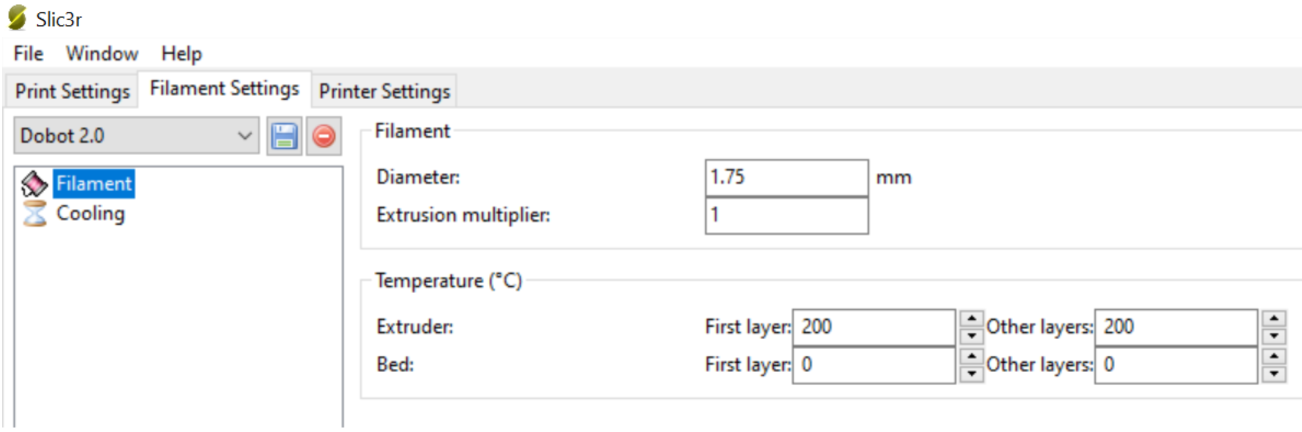
layers
Only infill where needed:

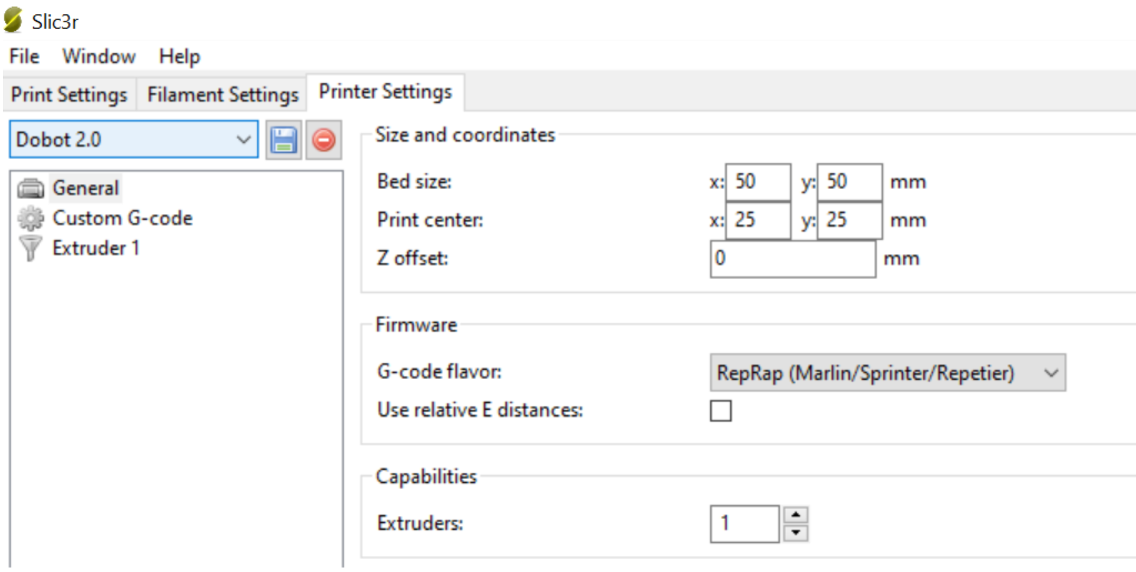
Appendix 2

FILAMENT SETTINGS OF 3D PRINTING IN REPETIER HOST SOFTWARE



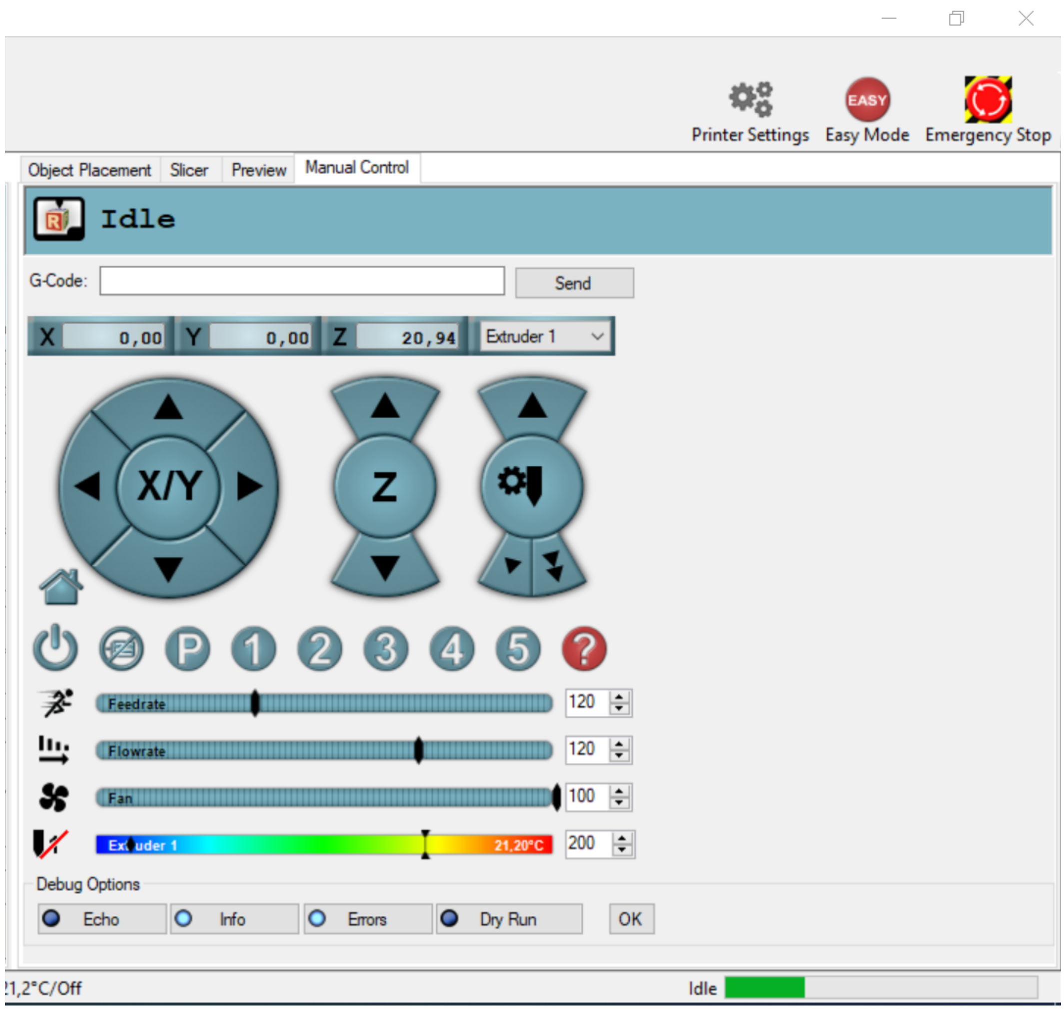
Appendix 3

PRINTER SETTINGS OF 3D PRINTING IN REPETIER HOST SOFTWARE



Appendix 4

TEMPERATURE, FEED-RATE AND FLOWRATE SETTINGS OF PRINTING NOZZLE



Appendix 5

SIMULATION OF 3D PRINTING PROCESS IN REPETIER HOST SOFTWARE